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CALIBRATION OF FOUR CONICALLY TIPPED FLOW SURVEY RAKES AT TRANSONIC SPEEDS

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Propulsion Wind Tunnel Facility
ARO, Inc.

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ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

NOTICES

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a subsidiary of Sverdrup and Parcel, Inc.

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ABSTRACT

Four flow survey rakes with one, two, four, and eight, 40-deg conically tipped probes were calibrated in the Transonic Model Tunnel of the Propulsion Wind Tunnel Facility to establish pressure coefficient characteristics at selected Mach numbers and angles of attack and to determine whether intra-probe interference existed at transonic speeds. The calibration was conducted at Mach numbers from 0.70 to 1.40 and angles of attack from -10 to +15 deg. The Reynolds number based on cone maximum diameter varied from 0.14 to 0.17 million.

The results showed that pressure differences measured by diametrically opposed orifices were linear with angle of attack for all rake configurations. Total pressures and average static pressures measured on the probes decreased with increasing angle of attack. The two- and four-probe configurations showed no interference effects, and the eight-probe configuration indicated interference effects at all test Mach numbers.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

A. Lincoln Coapman
Major, USAF
Acting AF Representative, PWT
DCS/Test

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ILLUSTRATIONS

NOMENCLATURE

C_{p_α}	Coefficient of the differential pressure between orifices 3 and 1, $\frac{p_{s3} - p_{s1}}{q_\infty}$ (see Fig. 2d)
D	Probe tip reference diameter, 0.03125 ft
M_∞	Free-stream Mach number
$\bar{p}$	Arithmetic mean of the four static pressures measured on one probe $\left[1/4(p_{s1} + p_{s2} + p_{s3} + p_{s4})\right]$, psf
p_s	Static pressure measured on cone surface, psf
p_t	Total (pitot) pressure measured at cone apex, psf
p_∞	Free-stream static pressure, psf
q_∞	Free-stream dynamic pressure, $0.7\, p_\infty M_\infty{}^2$, psf
Re	Reynolds number based on reference diameter, $\frac{V_\infty D}{\nu_\infty}$
V_∞	Free-stream velocity, ft/sec
α	Angle of attack, deg
γ	Angle of roll of probe tips, deg
ν_∞	Free-stream kinematic viscosity, ft^2/sec
ϕ	Angle of roll of rake, deg

SUBSCRIPTS

1, 2, 3, 4	Probe static orifice location
avg	Average of quantity measured by all probes on a rake configuration
α	Quantity measured at specified angle of attack
$\alpha = 0$	Quantity measured at zero angle of attack

1.0 INTRODUCTION

At the request of the Aeronautical Systems Division (ASD), Air Force Systems Command (AFSC), four flow survey rakes were calibrated for the General Dynamics Corporation in the Transonic Model Tunnel of the Propulsion Wind Tunnel Facility (PWT), Arnold Engineering Development Center (AEDC), AFSC. The calibration was conducted during the period from January 30 to February 7, 1963, and schlieren pictures were obtained on March 4, 1963.

The purposes of the calibration were (1) to determine the effect of angle of attack and Mach number on the total pressure and differential static pressure coefficients, (2) to determine the degree of probe misalignment in pitch and yaw, and (3) to determine whether intra-probe interference existed at transonic speeds. A similar calibration of one of the rake configurations was conducted at supersonic speeds in the von Kármán Gas Dynamics Facility, AEDC, and is reported in Ref. 1.

2.0 APPARATUS

2.1 TEST FACILITY

The Transonic Model Tunnel is an open-circuit, continuous-flow wind tunnel capable of operation at Mach numbers from 0.50 to 1.50. The test section is 12 in. by 12 in. in cross section and 37.5 in. long. A more detailed description of the tunnel, equipment, and calibration may be found in Refs. 2 and 3.

The test section wall configuration, consisting of four perforated plates, and the rake location in the test section are shown schematically in Fig. 1.

2.2 TEST ARTICLES

Details of the flow survey rakes are shown in Fig. 2, and photographs of two of the rake configurations are presented in Fig. 3.

The flow survey rakes consisted of single-, two-, four-, and eight-probe configurations. The two-probe rake (Fig. 2a) was constructed such that probe No. 2 could be removed, resulting in a

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single-probe rake. The probes on the four- and eight-probe rakes (Figs. 2b and 2c) were mounted on pylons attached to the rake strut. The plane passing through orifices 1 and 3 (top and bottom) on all probes was at a -3° 20' roll angle to the normal to the strut. Therefore during this calibration the entire rake was rolled +3° 20' to place the orifices in the pitch and yaw reference planes.

The probe tip details are shown in Fig. 2d. The probe tips were cones having a 40-deg included angle. The static orifices were located at 90-deg intervals on the cone surface 48 percent of the cone length aft of the total pressure orifice at the cone apex. The lip at the entry of the total pressure orifice was made sharp (0.002-in. thick) because previous experience indicated that sharp lips extend the angle-of-attack range through which total pressure measurements remain constant. The probe tips could be rolled ±180 deg in 90-deg increments about the probe longitudinal axis.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS AND PROCEDURE

The flow survey rakes were installed in the tunnel with the static orifices in the pitch and yaw planes. Angles of attack from 0 to 15 deg were obtained by using a 5.5-deg offset sting to augment the normal pitch range of the angle-of-attack mechanism. The entire rake was rolled 180 deg and pitched in a positive direction up to 10 deg angle of attack. At each of the roll positions (ϕ = 0 and 180 deg) the probe tips were rolled 180 deg.

The probe tips were calibrated in yaw by rolling the tips +90 and -90 deg and following the same pitch procedure that was used to calibrate the pitch plane orifices.

The eight-probe rake was calibrated at Mach numbers 0.70, 0.85, and 1.40. In addition, it was also tested at an orientation of $\phi = 0$, $\gamma = -90$ at Mach number 1.20. The one-, two-, and four-probe rakes were calibrated at Mach numbers 0.70, 0.85, 0.95, and 1.20. The tunnel stagnation pressure, which varies with atmospheric pressure and test section Mach number, ranged from 2800 to 2955 psf. Total temperature was maintained at approximately 150°F up to Mach number 0.95 and was increased to a maximum of 185°F at Mach number 1.40. The Reynolds number variation is shown in Fig. 4.

Rake pressures were connected to a multi-tube manometer and photographically recorded at each test condition for off-line data reduction.

3.2 PRECISION OF MEASUREMENTS

The following uncertainties in the data were calculated taking into consideration probable inaccuracies in probe pressure measurements and setting of tunnel conditions:

M_∞	C_{p_α}	$\bar{p}/p_t$
0.70	±0.0014	±0.0018
0.85	±0.011	±0.0017
0.95	±0.010	±0.0017
1.20	±0.008	±0.0015
1.40	±0.008	±0.0013

The most recent calibration of the tunnel (Ref. 3) showed that the Mach number deviations in the portion of the test section occupied by the rakes were within ±0.003 for $M_\infty \leq 1.0$ and ±0.015 for $M_\infty > 1.0$. The inaccuracy in setting angle of attack was estimated to be ±0.10 deg. The inaccuracy in measurement of local p_t was estimated to be ±7 psf for all test conditions.

4.0 RESULTS AND DISCUSSION

In the presentation of the test results, only data from the pitch plane orifice calibration are presented since yaw plane data were found to have similar characteristics. Also, data are presented only for γ = 0 and 180 for ϕ = 0. Data obtained at γ = 0 and 180 for ϕ = 180 agreed in slope, $dC_{p_\alpha}/d\alpha$, but not in magnitude with the data obtained at ϕ = 0. The difference was possibly caused by either probe misalignment or differences in the flow angularity sensed by the probe tips. In the latter instance, recent unpublished data from a flow angularity study in the Transonic Model Tunnel indicate that an upward flow exists in the test section and that the magnitude of the flow angularity is not constant in a cross-sectional plane through the test section. Therefore, when the rakes were tested at the different roll angles (ϕ = 0 and 180 deg), the probes were subjected to two different flow fields. Because of this, it is not possible to eliminate flow angularity from the data or to evaluate the probe misalignments. The data presented are indicative only of the alignment of the probe tip with respect to its own roll axis.

Typical variations of C_{p_α} with angle of attack are presented in Fig. 5. Since the data obtained from probe 1 of each rake were representative of the data obtained from the other probes, only data from probe 1 of each rake are presented. For all probes, the variation of C_{p_α} with α was linear throughout the angle-of-attack range of the test. The trends of the $\gamma = 0$ and 180 curves indicate that they would intersect on the negative angle-of-attack axis. This indicates that the probe tips of all rakes were aligned with respect to their own roll axis and that the negative angle exhibited by the extrapolated intersection was probably caused mainly by flow angularity.

The variation of $p_{t_\alpha}/p_{t_{\alpha=0}}$ with α is presented in Fig. 6 for the four rake configurations. At $\alpha = 0$ the total pressure sensed by the probes was, within the accuracy of the data, equal to free-stream total pressure at $M_\infty \leq 1.0$, and equal to the values predicted by the normal shock relationship at $M_\infty > 1.0$. As angle of attack was varied to 10 deg, the total pressure sensed by the probes was 99.5 percent of p_t at $\alpha = 0$, and as α increased to +15 deg the probe total pressure was 98 percent of p_t at $\alpha = 0$.

The variations of the ratio of average probe static pressure to probe total pressure with angle of attack for the four rakes are presented in Fig. 7. The average static pressure on the probes decreased with increasing angle of attack and was more pronounced with increasing Mach number up to 1.2. At $\alpha = 15$, $\bar{p}/p_t$ decreased as much as 4.5 percent from $\bar{p}/p_t$ at $\alpha = 0$ for the one-, two-, and four-probe rakes at $M_\infty = 1.2$. Although no interference effects are evident in the data from the two- and four-probe rakes, the data from the eight-probe rake present greater differences between the individual probes than can be attributed to normal data scatter. Schlieren pictures of the eight-probe rake presented in Fig. 8 indicate that at $M_\infty \geq 0.85$, intra-probe interference existed that would affect the static pressure measurements.

The variations of $(\bar{p}/p_t)_{avg}$ with Mach number are presented in Fig. 9 for constant angles of attack of 0, 8, and 12 deg. The data presented from the eight-probe rake were obtained at an orientation of $\phi = 0$ and $\gamma = -90$ because that was the only orientation where data were obtained at four Mach numbers. Also shown in Fig. 9d is the theoretical variation of $(\bar{p}/p_t)$ for Mach numbers greater than that for which shock attachment occurs for a cone semi-angle of 20 deg. As shown in Figs. 7 and 9, significant variations occurred in $\bar{p}/p_t$ with angle of attack at $M_\infty \leq 1.20$. For the eight-probe rake, the differences decreased as Mach number was increased to 1.40. If the curves for the eight-probe rake are extrapolated to the Mach number for shock attachment (Fig. 9d), the $\alpha = 0$ data are in perfect agreement with the theoretical values for $\alpha = 0$ to $M_\infty = 1.40$.

5.0 CONCLUSIONS

The following conclusions have been drawn from the results obtained during the calibration of the four flow survey rakes:

1. Differential pressure coefficients obtained from all rake configurations were linear throughout the angle-of-attack range of the test.
2. Probe total pressure was 99.5 percent of p_t at $\alpha = 0$ as α was varied from $\alpha = 0$ to 10 deg. At $\alpha = +15$ deg, probe total pressure was 98 percent of p_t at $\alpha = 0$.
3. The average static pressure on the probes decreased with increasing angle of attack and was more pronounced with increasing Mach number up to 1.2.
4. The ratio of probe average static pressure to probe total pressure varied with both angle of attack and Mach number.
5. No interference effects were evident in data from the two- and four-probe rakes. The eight-probe rake showed interference effects in static pressure measurements at all Mach numbers investigated.

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1. Baer, A. L. "Calibration Characteristics of a Flow Survey Rake of Eight 40-deg Cone-Cylinder Probes." AEDC-TDR-63-97, May 1963.
2. Test Facilities Handbook, (4th Edition). "Propulsion Wind Tunnel Facility, Vol. 3." Arnold Engineering Development Center, July 1962.
3. Nichols, J. H. and Jackson, F. M. "A Check Calibration of the AEDC-PWT Transonic Model Tunnel." AEDC-TDR-62-206, October 1962.

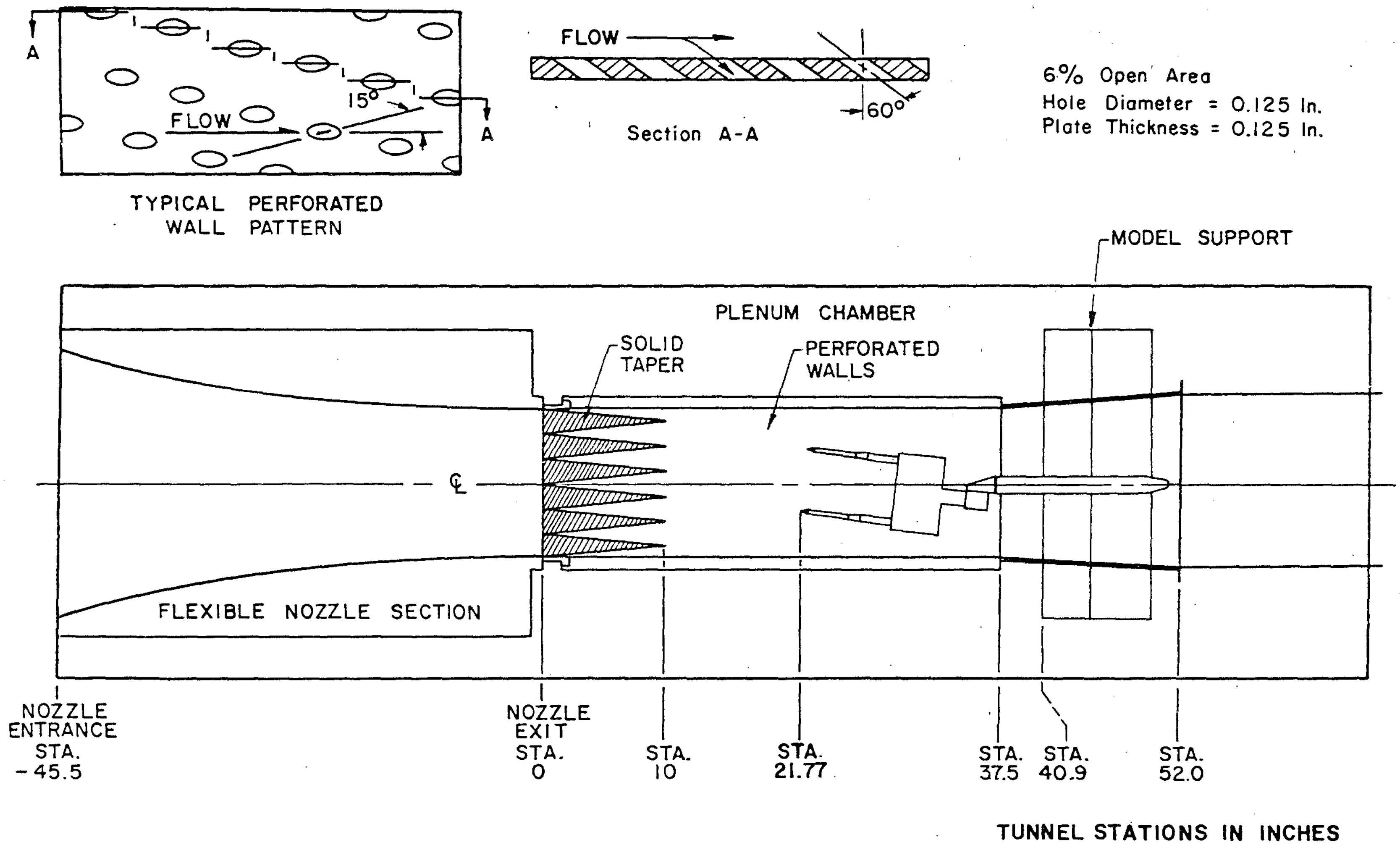
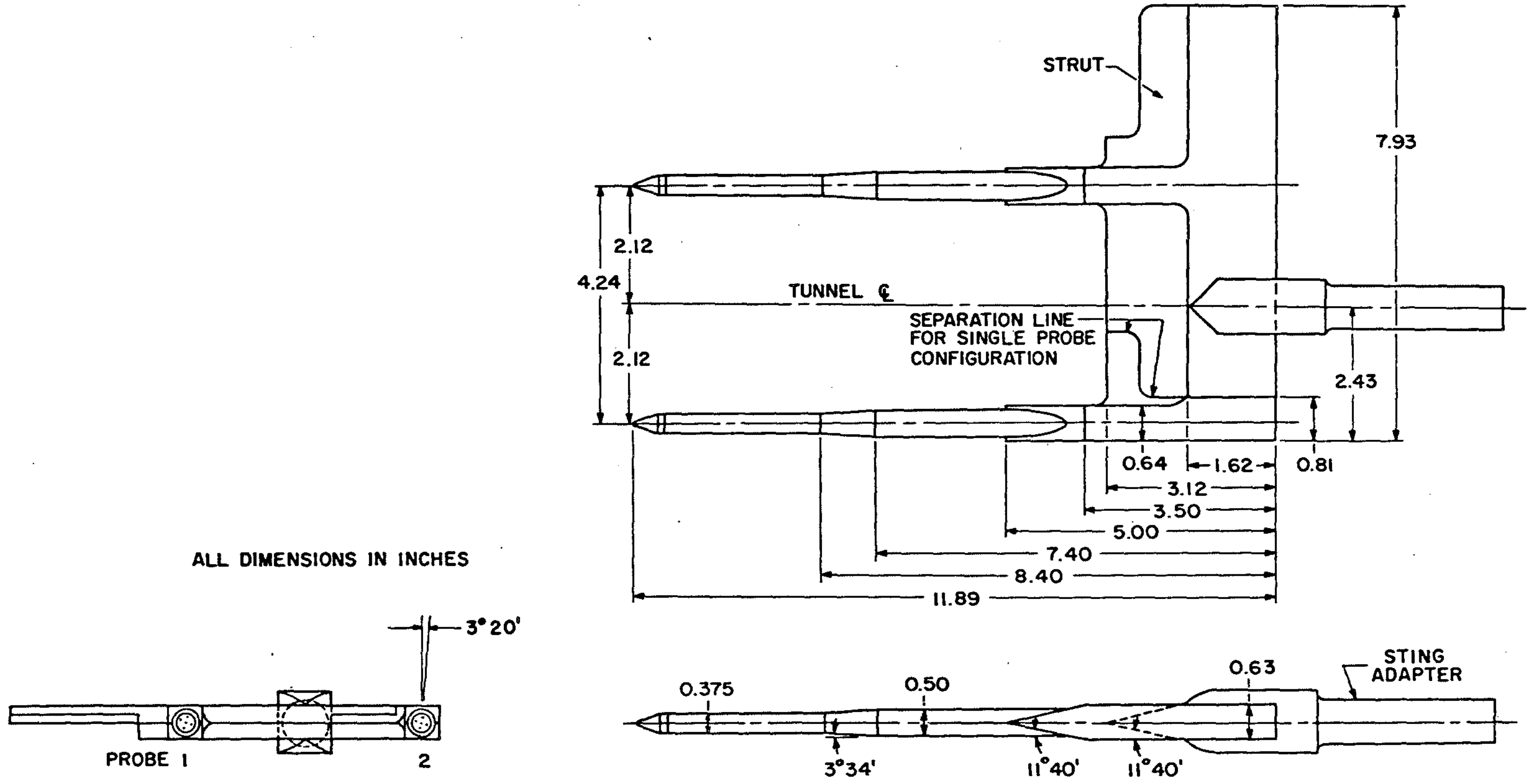
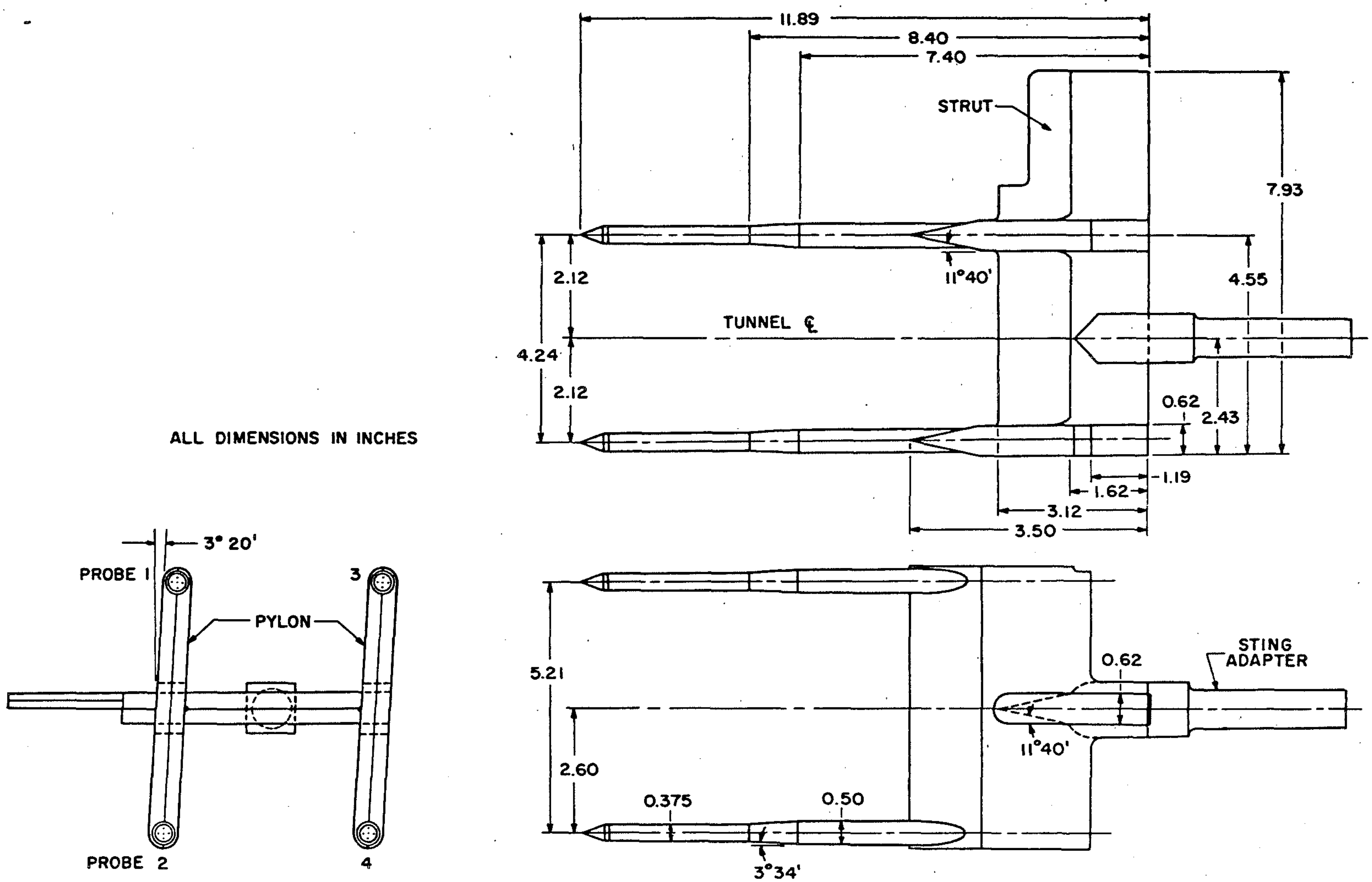


Fig. 1 Schematic of Transonic Model Tunnel Showing Wall Geometry and Rake Locations



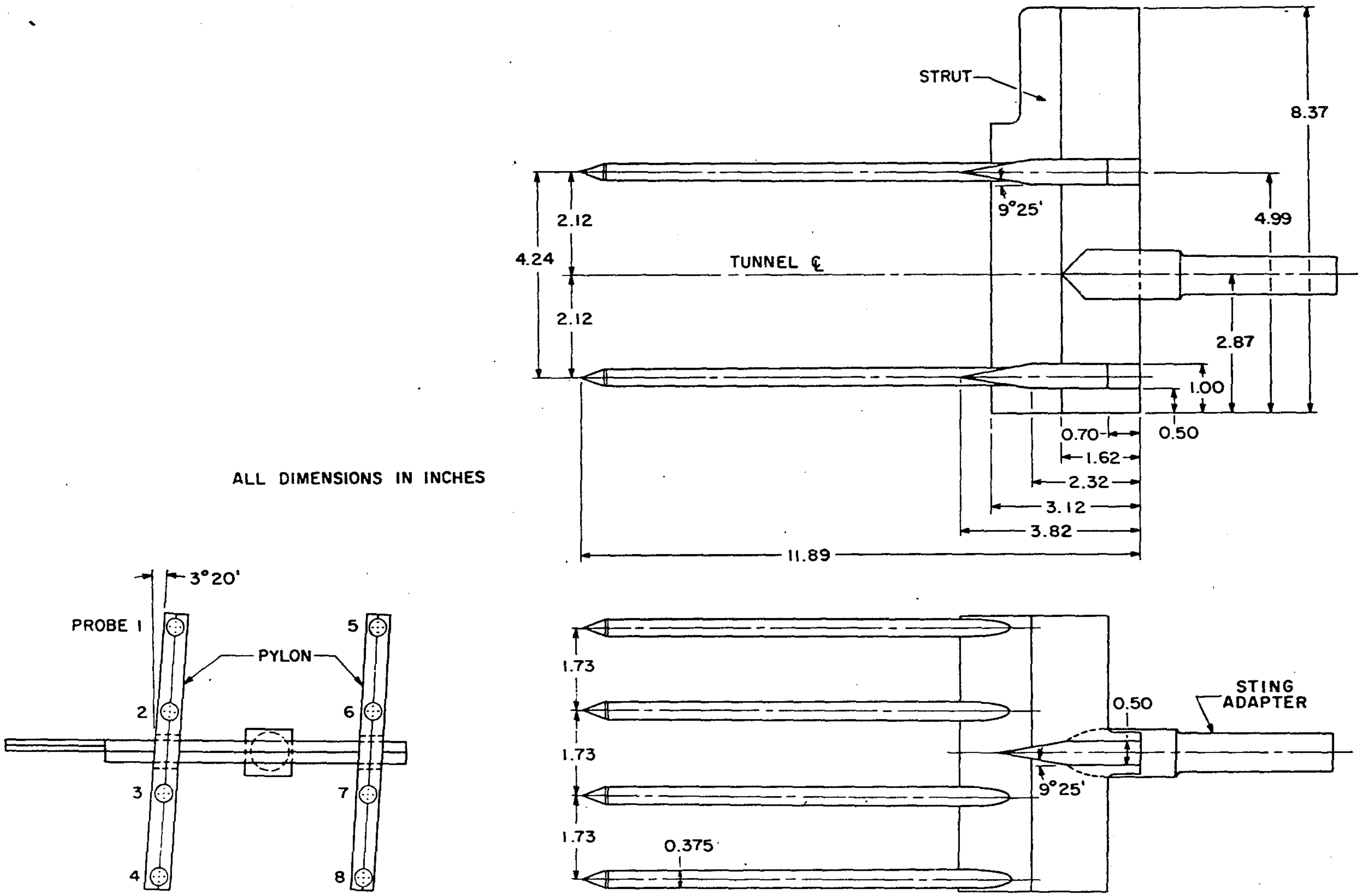
a. Single-Probe and Two-Probe Rakes

Fig. 2 Rake Details and Dimensions



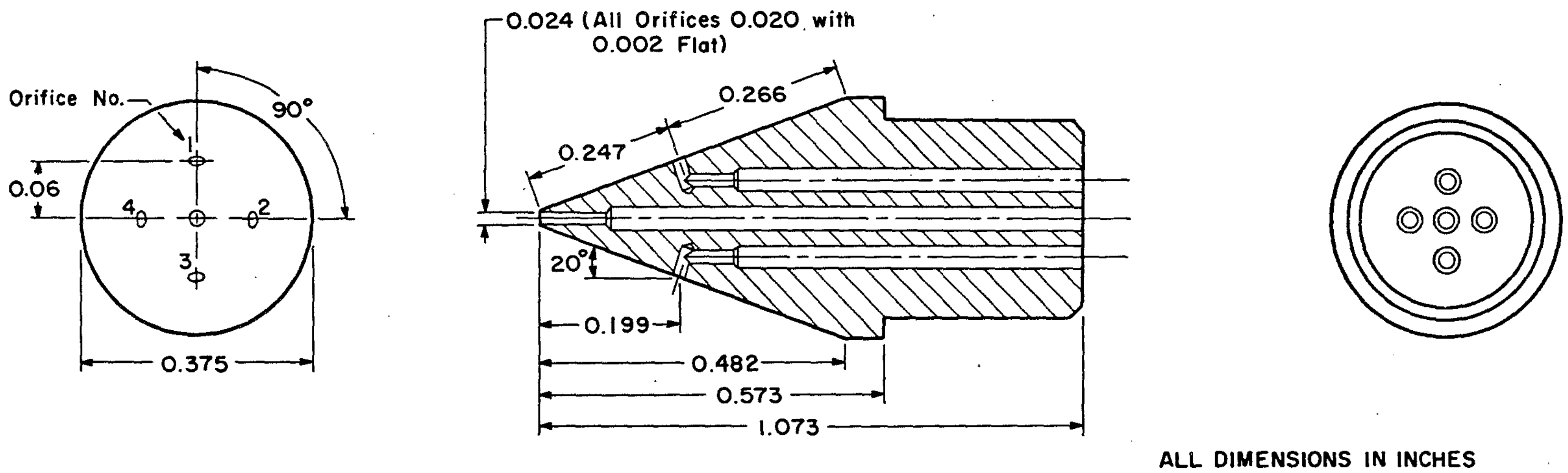
b. Four-Probe Rake

Fig. 2 Continued



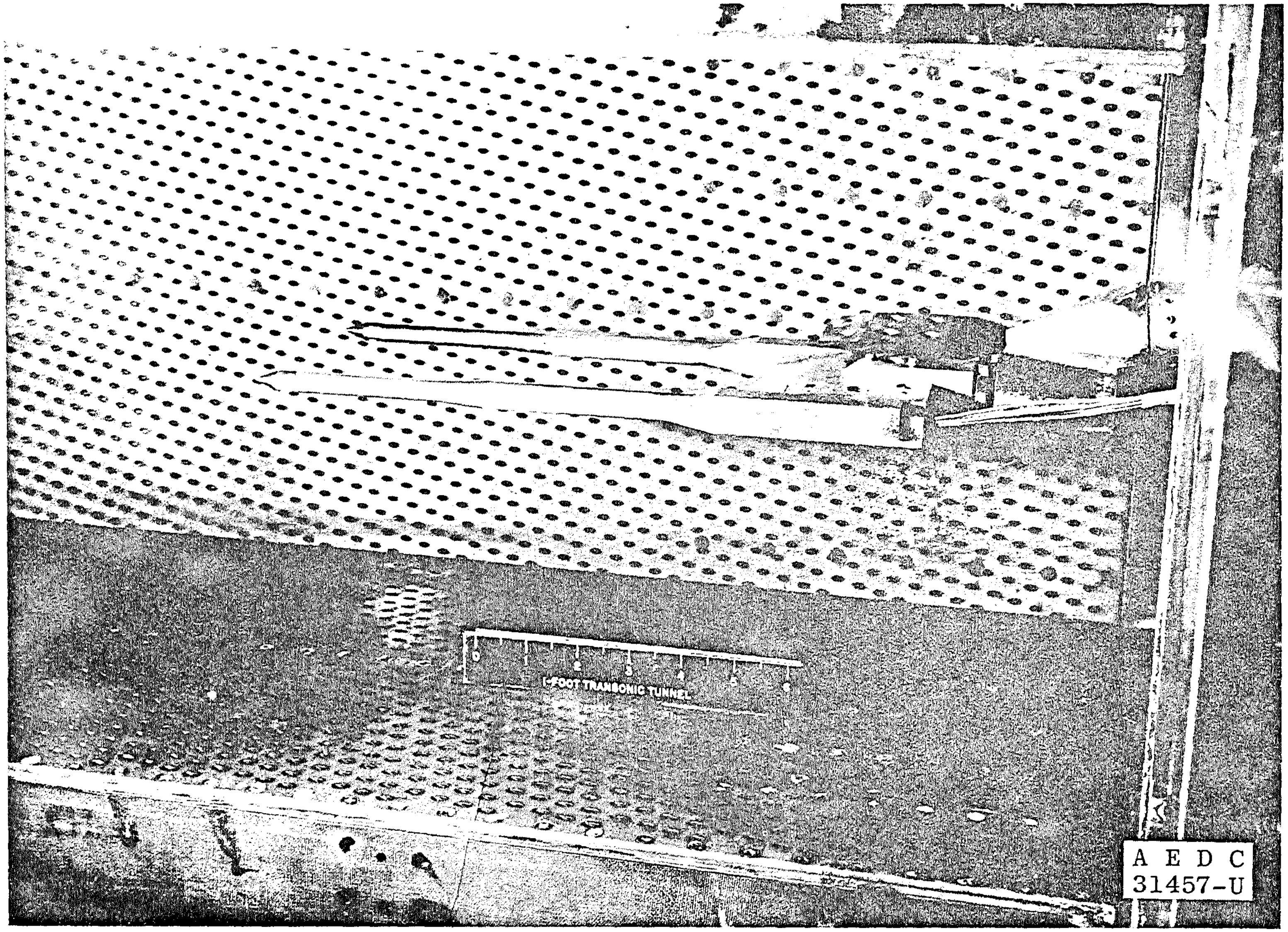
c. Eight-Probe Rake

Fig. 2 Continued



d. Rake Tip Details
Fig. 2 Concluded

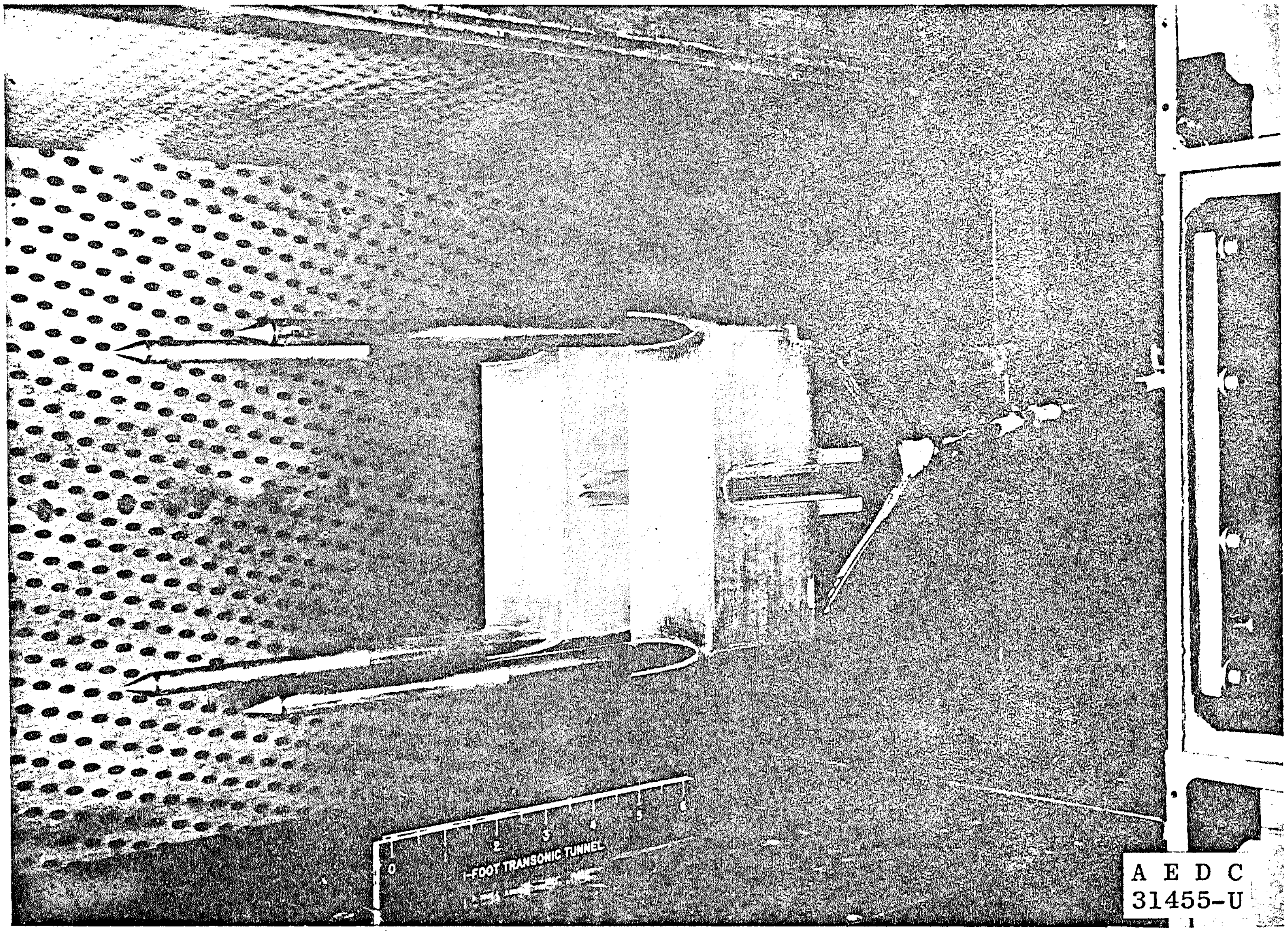
.515



a. Two-Probe Rake

Fig. 3 Photographs of Rake Installations

Fig. 3 Photographs of Rake Installations



b. Four-Probe Rake
Fig. 3 Concluded

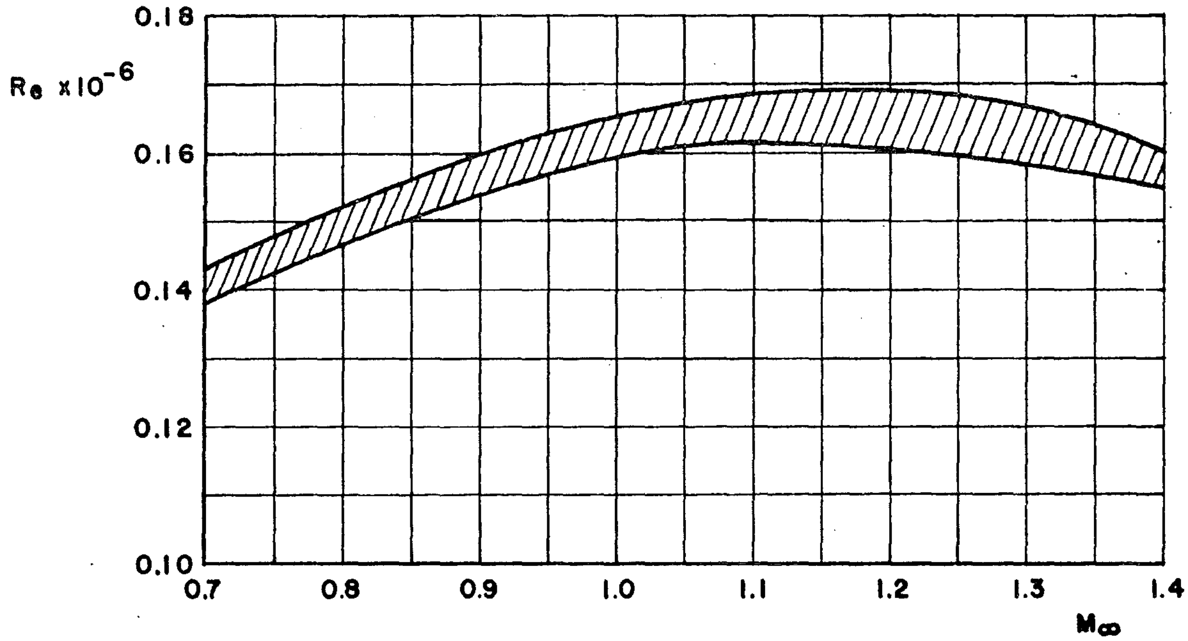
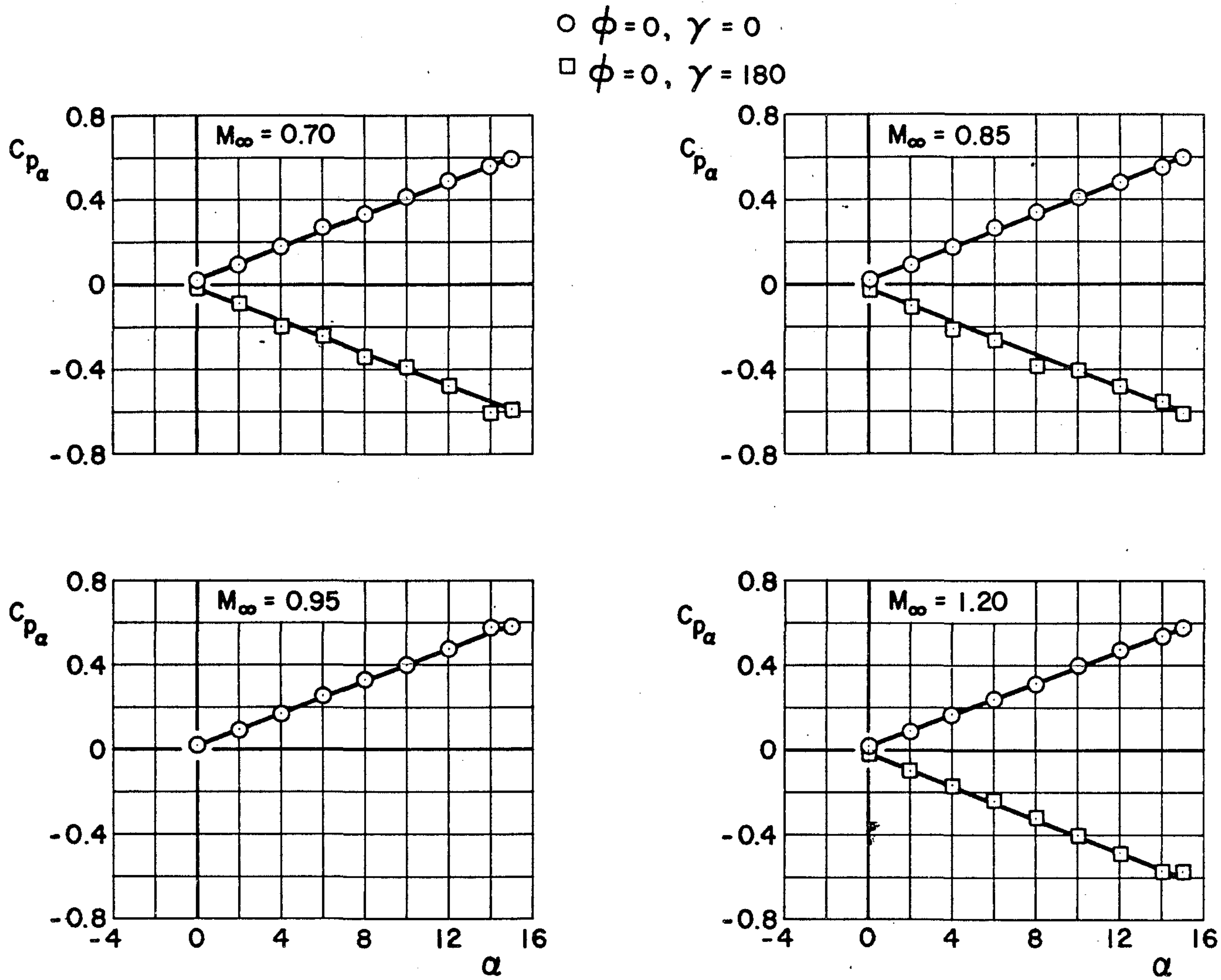
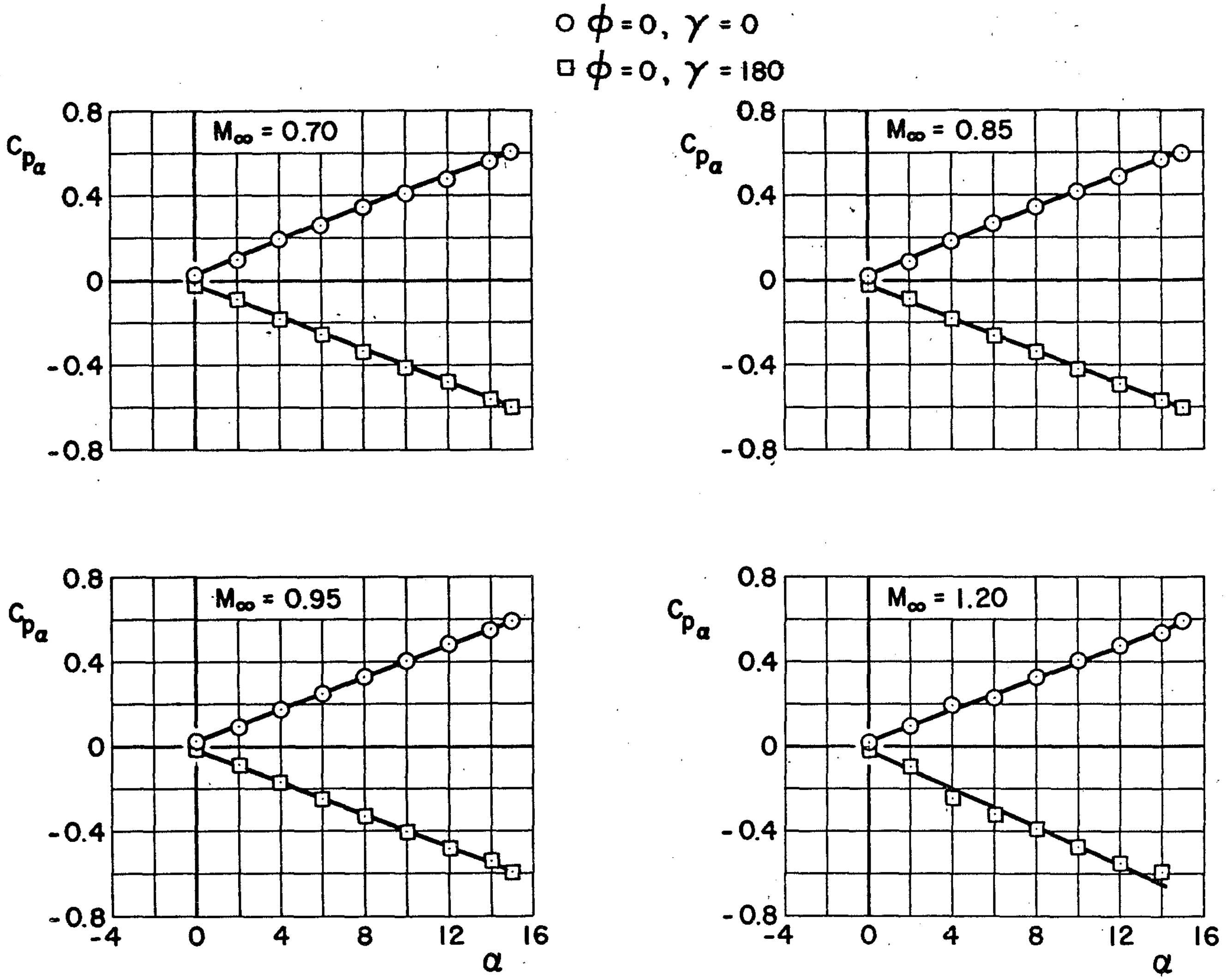


Fig. 4 Variation of Test Reynolds Number with Mach Number



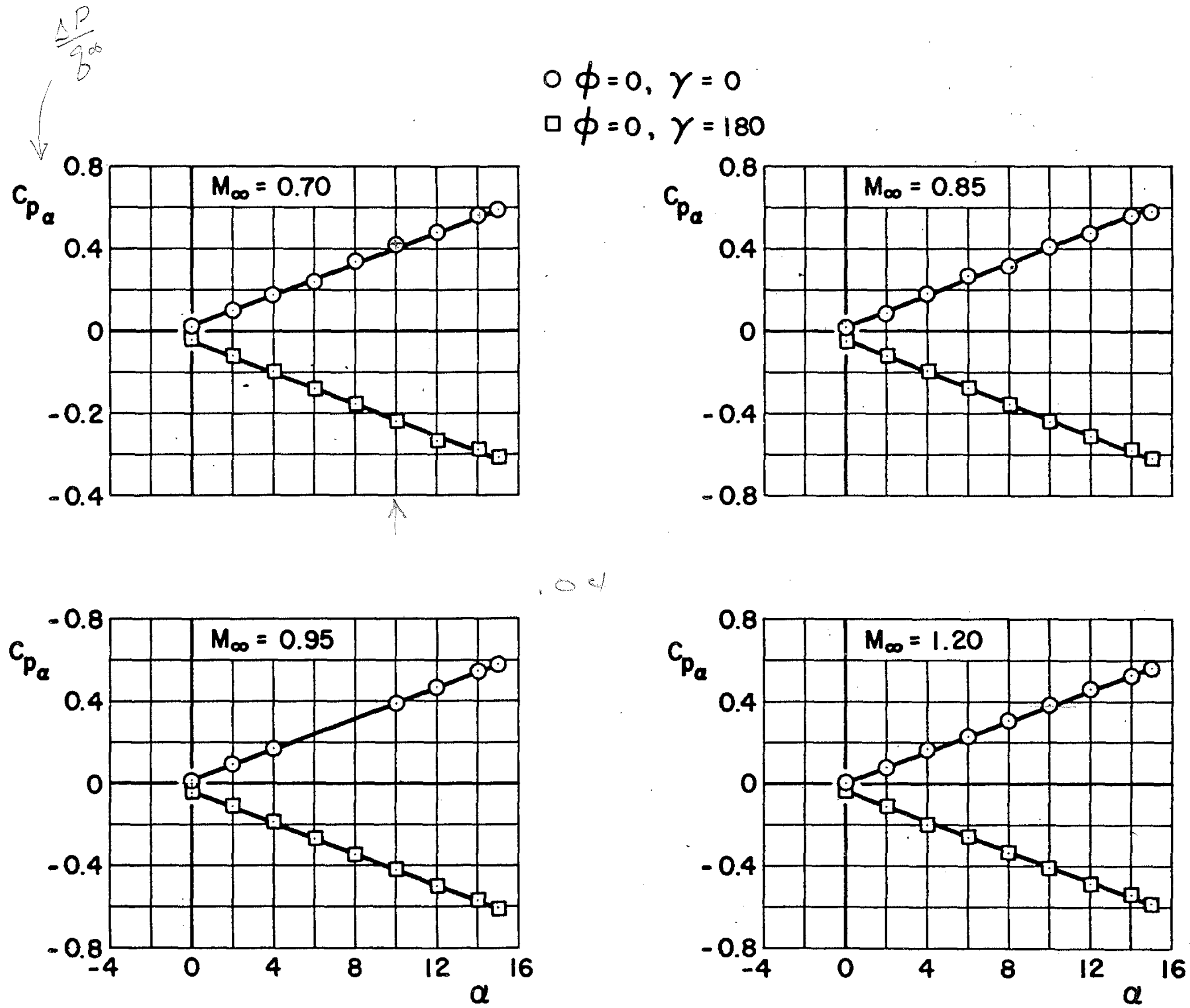
a. Single-Probe Configuration

Fig. 5 Variation of Pitch Plane Pressure Differential with Angle of Attack



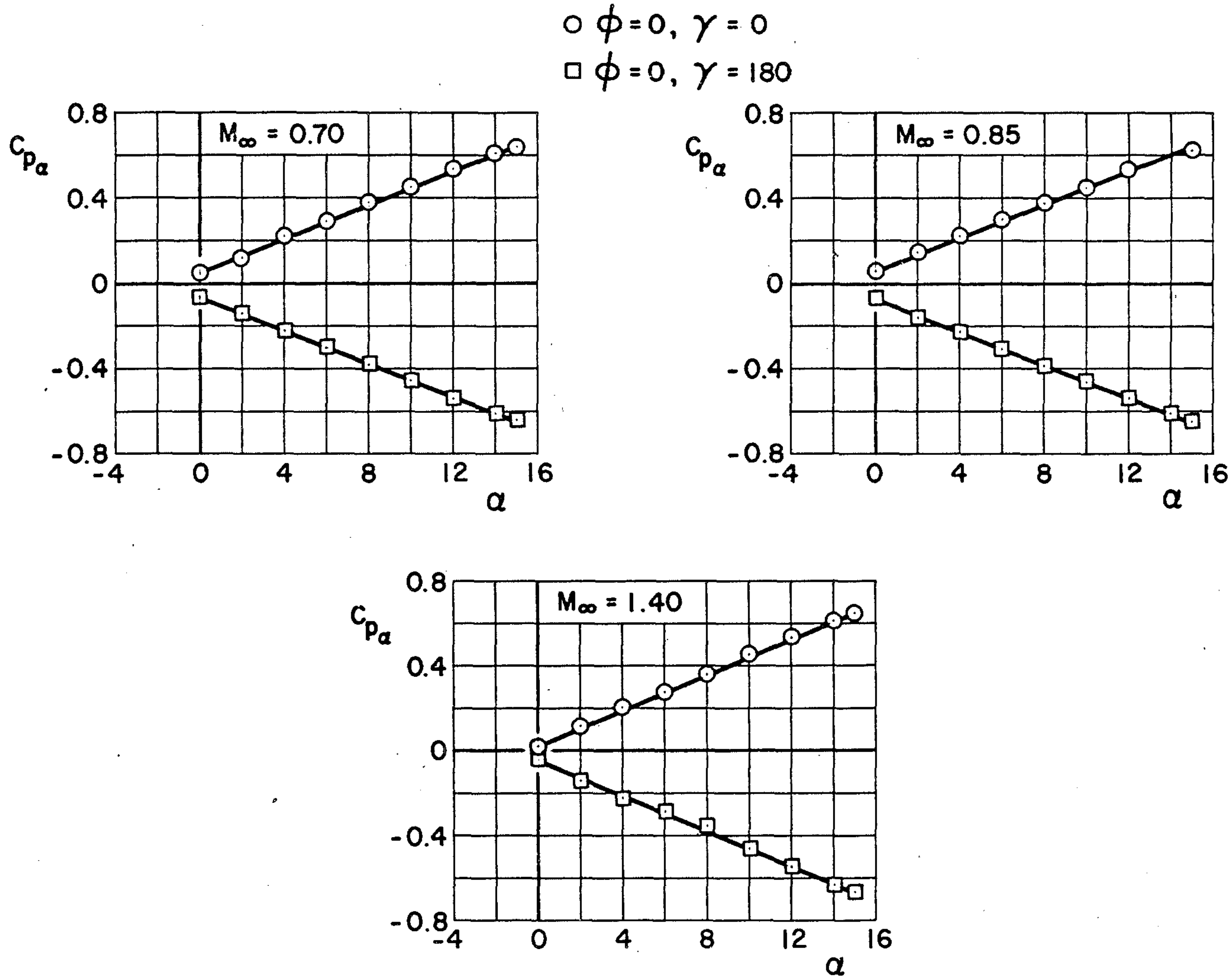
b. Probe One of Two-Probe Configuration

Fig. 5 Continued



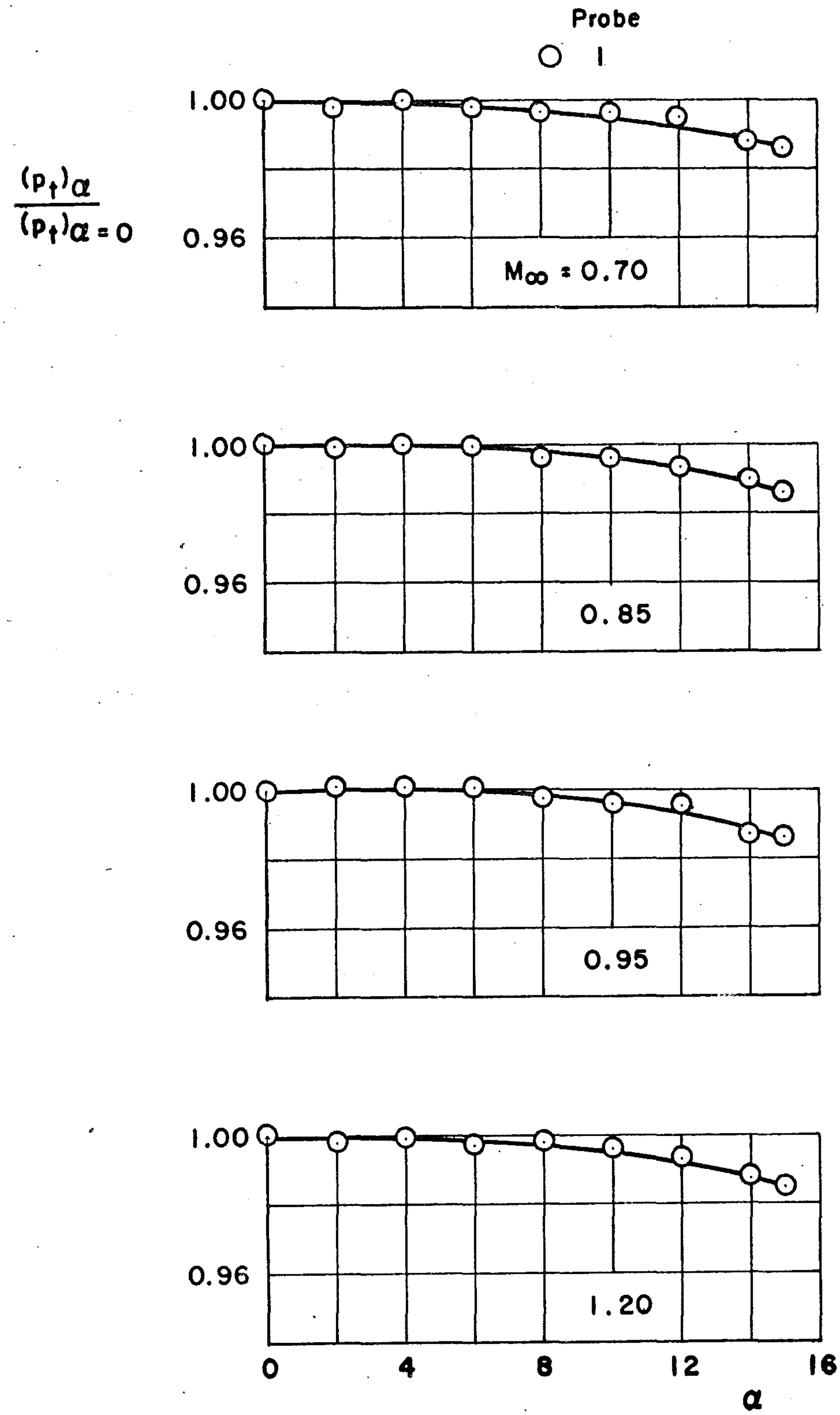
c. Probe One of Four-Probe Configuration

Fig. 5 Continued



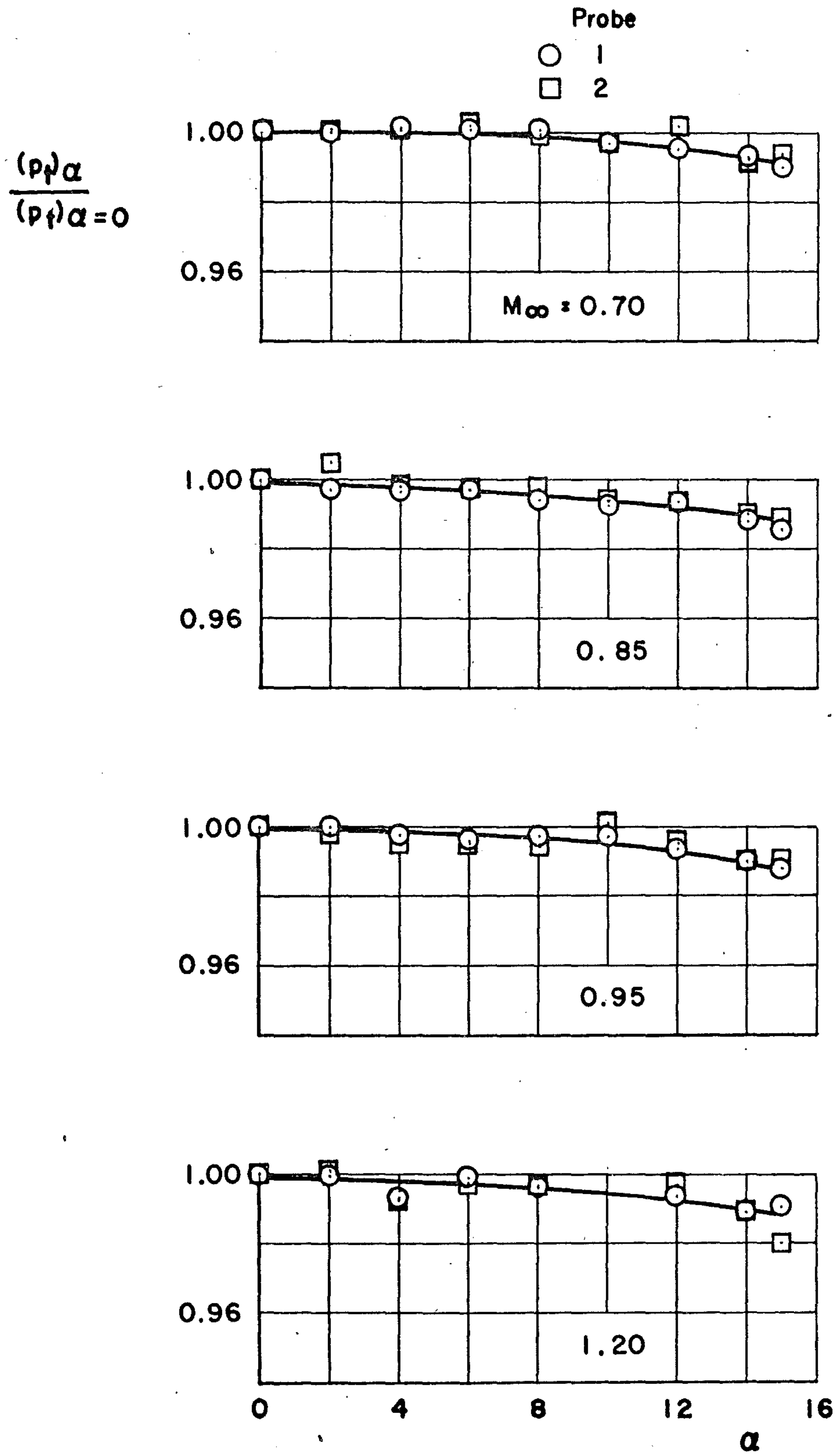
d. Probe One of Eight-Probe Configuration

Fig. 5 Concluded



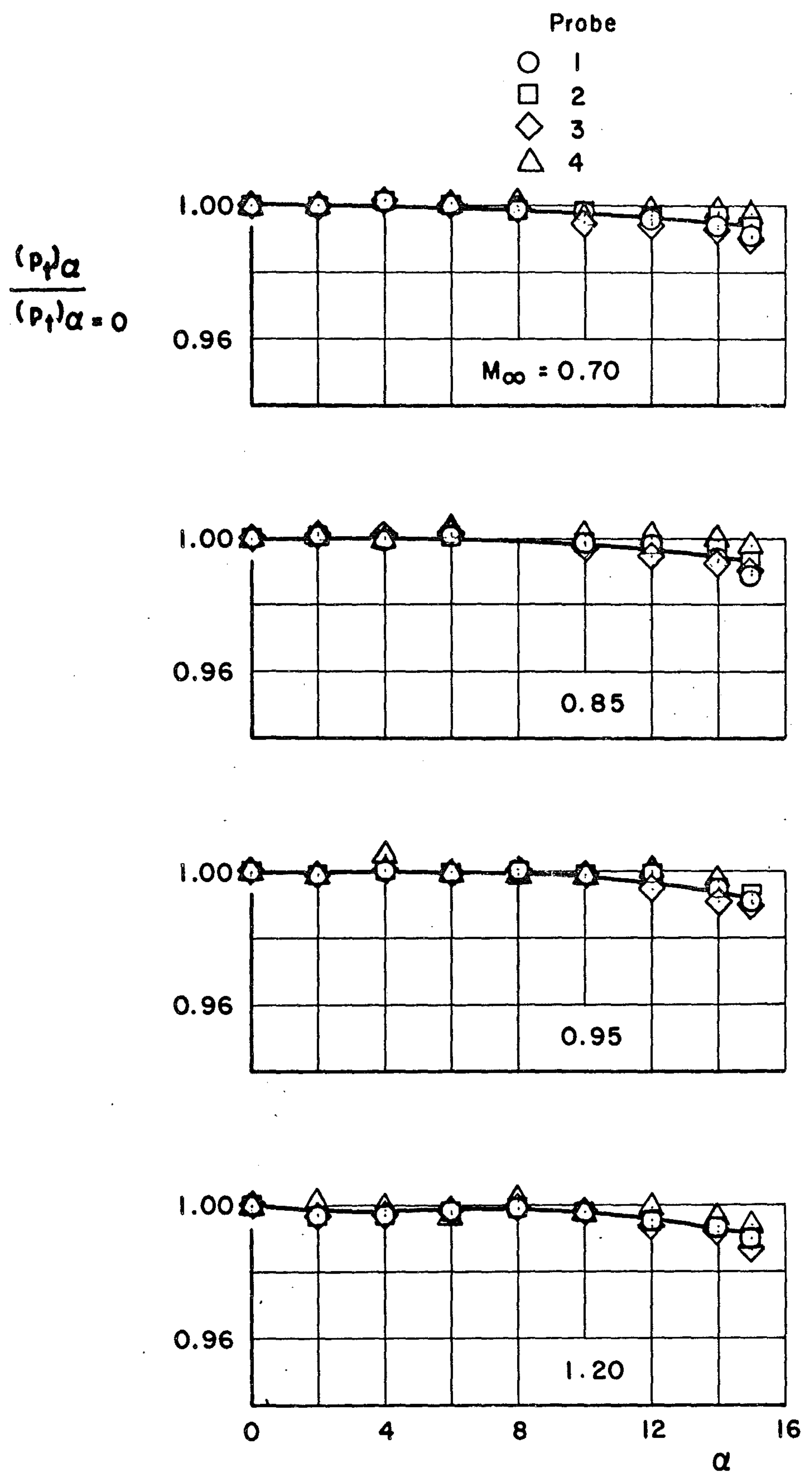
a. Single-Probe Configuration

Fig. 6 Variation of Probe Total Pressure with Angle of Attack

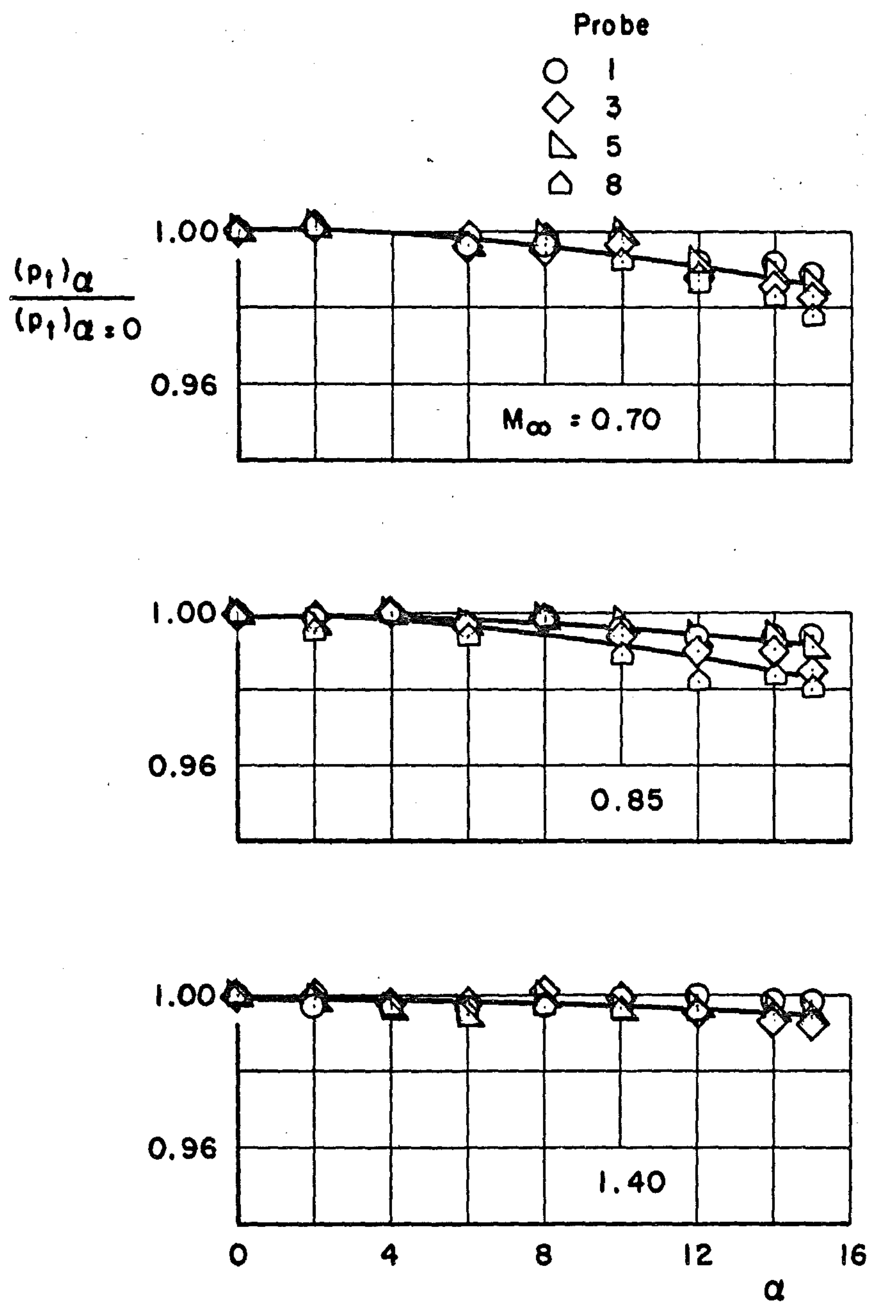


b. Two-Probe Configuration

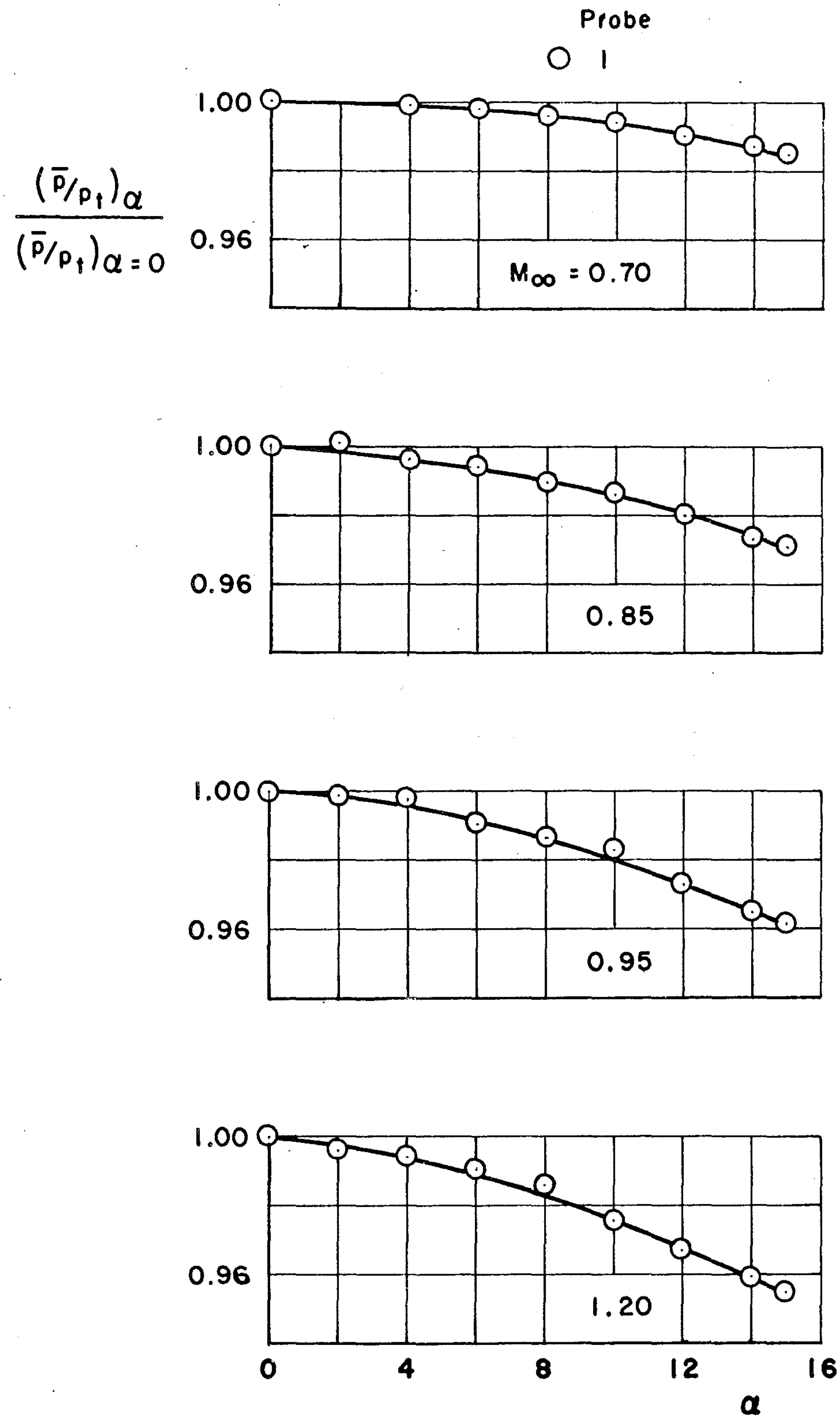
Fig. 6 Continued



c. Four-Probe Configuration
Fig. 6 Continued

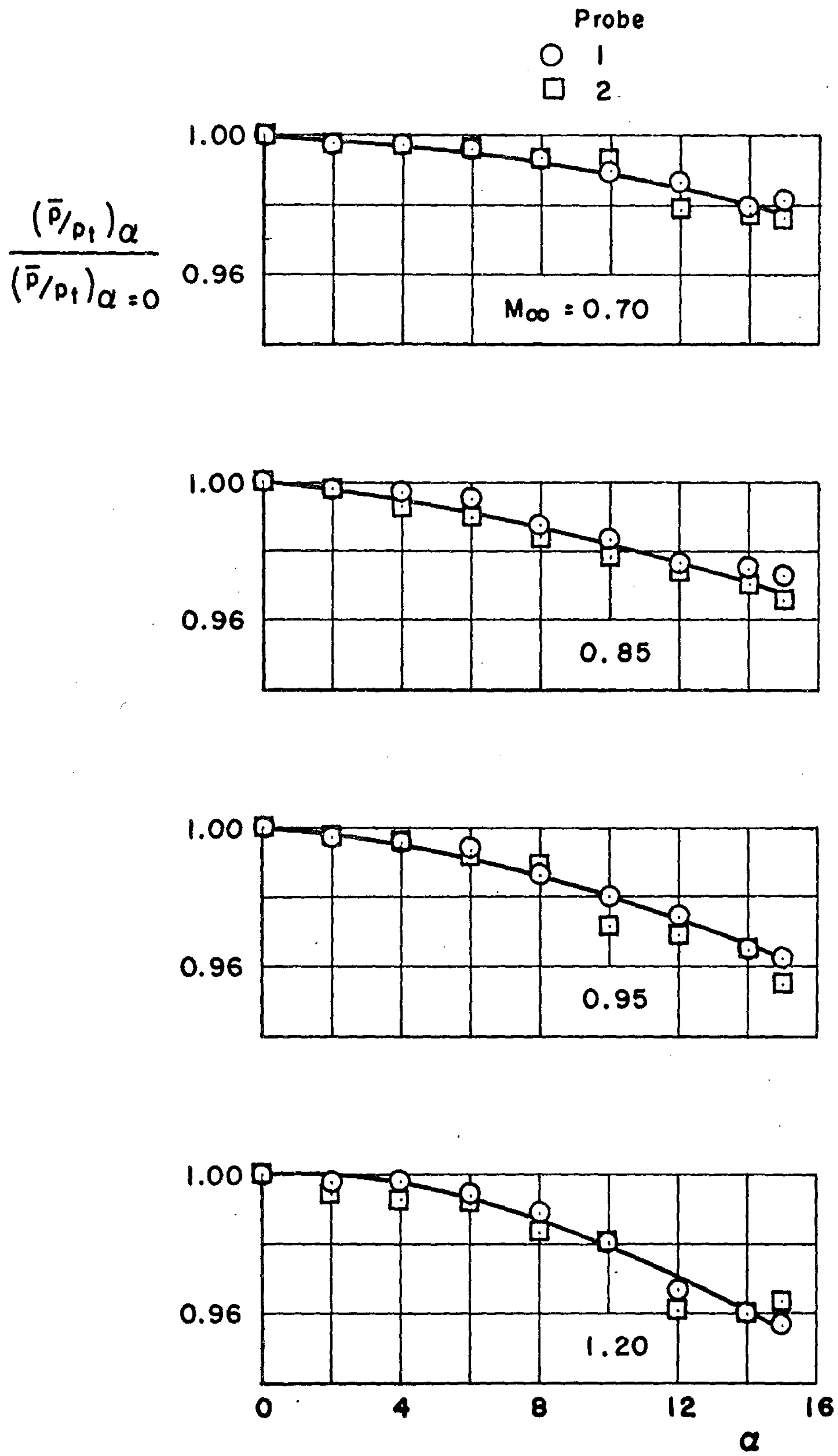


d. Eight-Probe Configuration
Fig. 6 Concluded



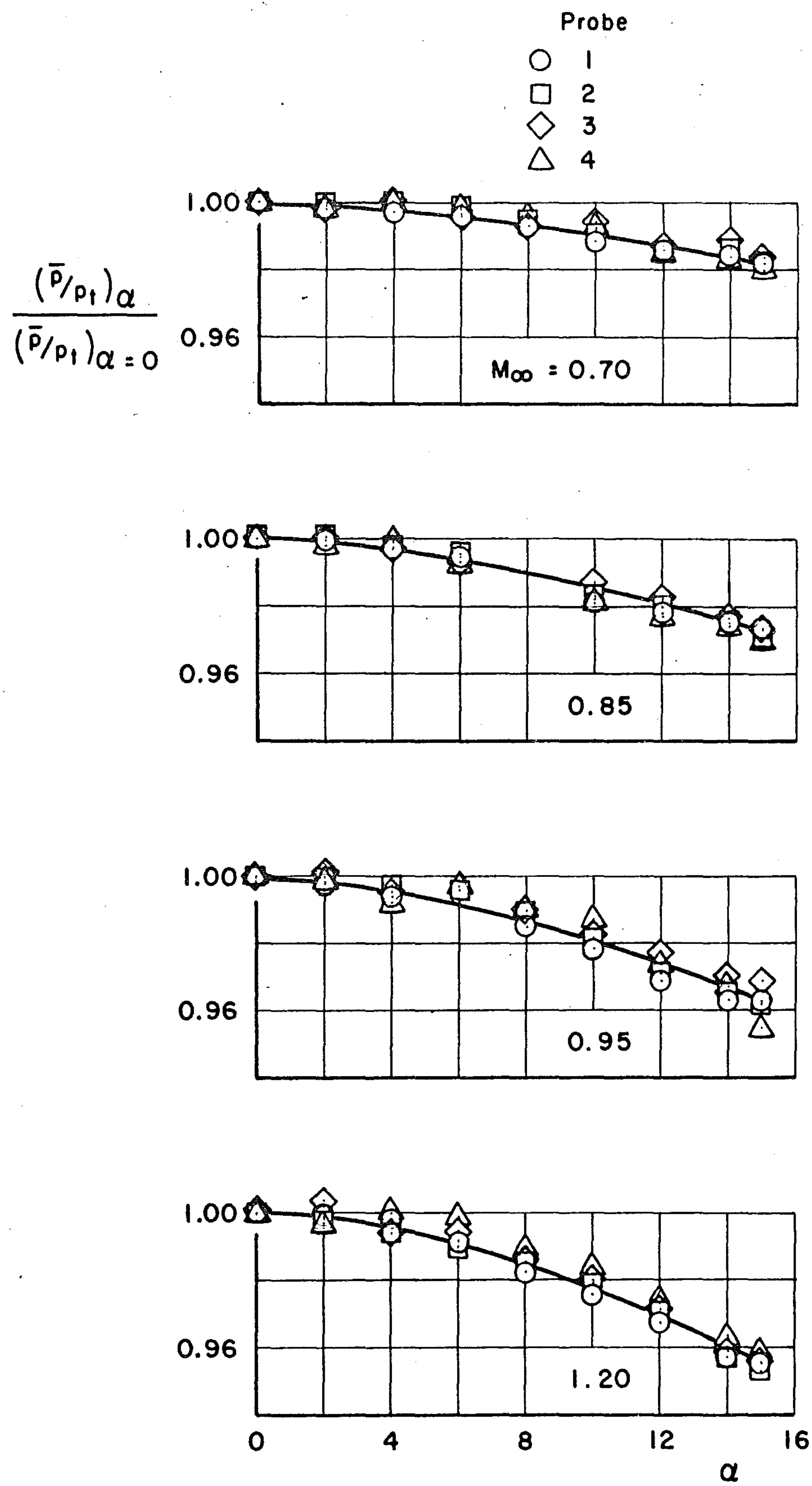
a. Single-Probe Configuration

Fig. 7 Variation of Ratio of Average Probe Static Pressure to Probe Total Pressure with Angle of Attack

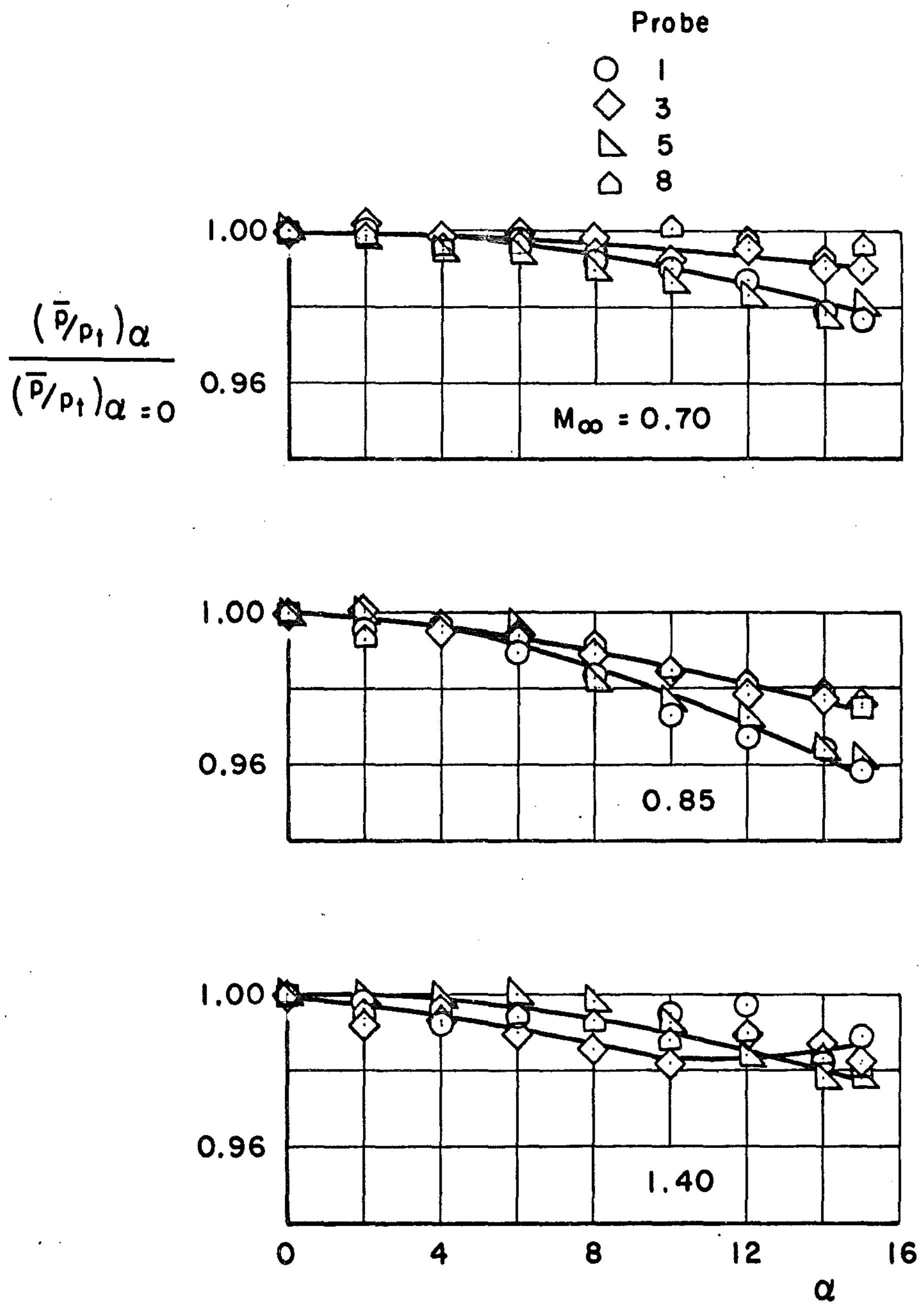


b. Two-Probe Configuration

Fig. 7 Continued



c. Four-Probe Configuration
Fig. 7 Continued



d. Eight-Probe Configuration

Fig. 7 Concluded

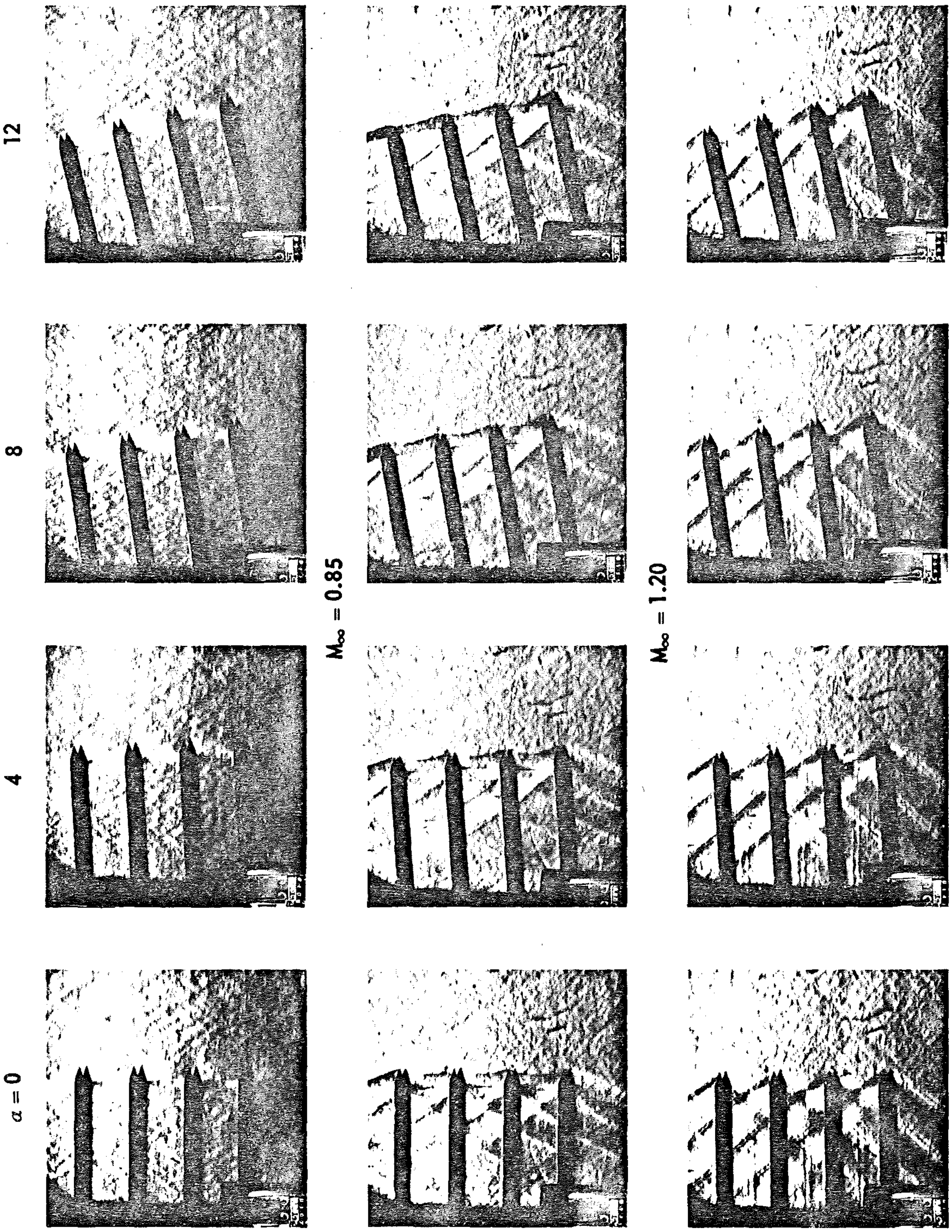
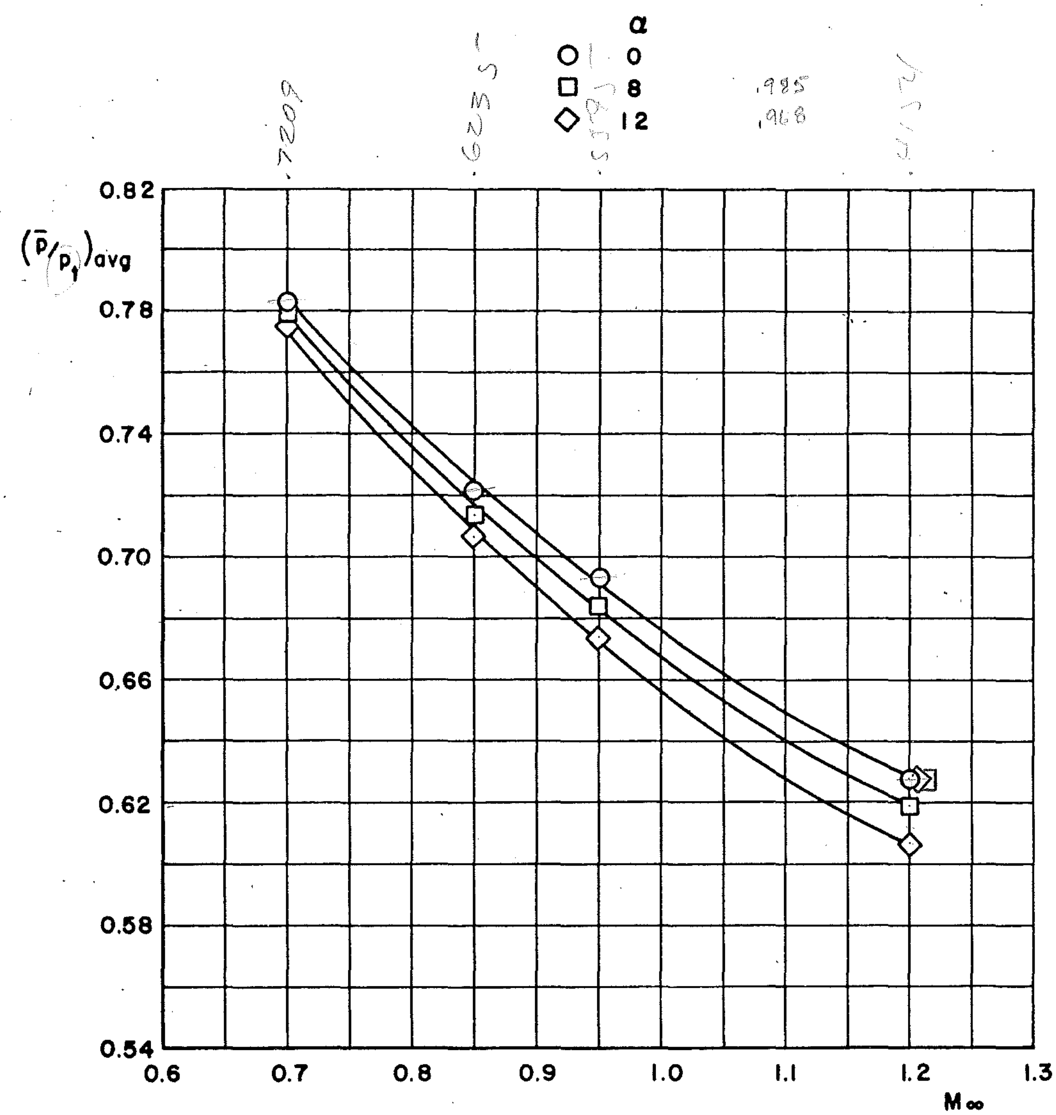
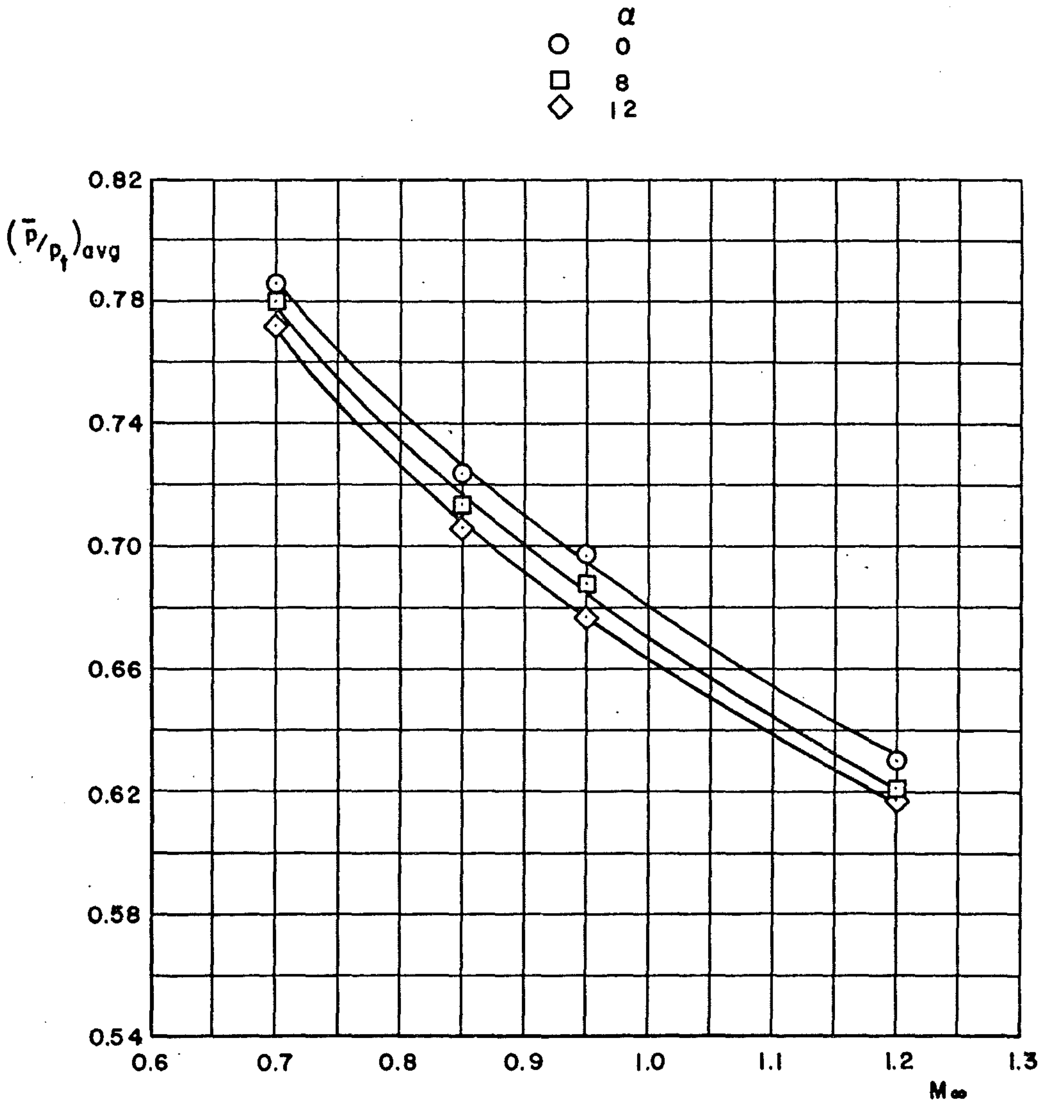


Fig. 8 Schlieren Pictures of Eight-Probe Rake



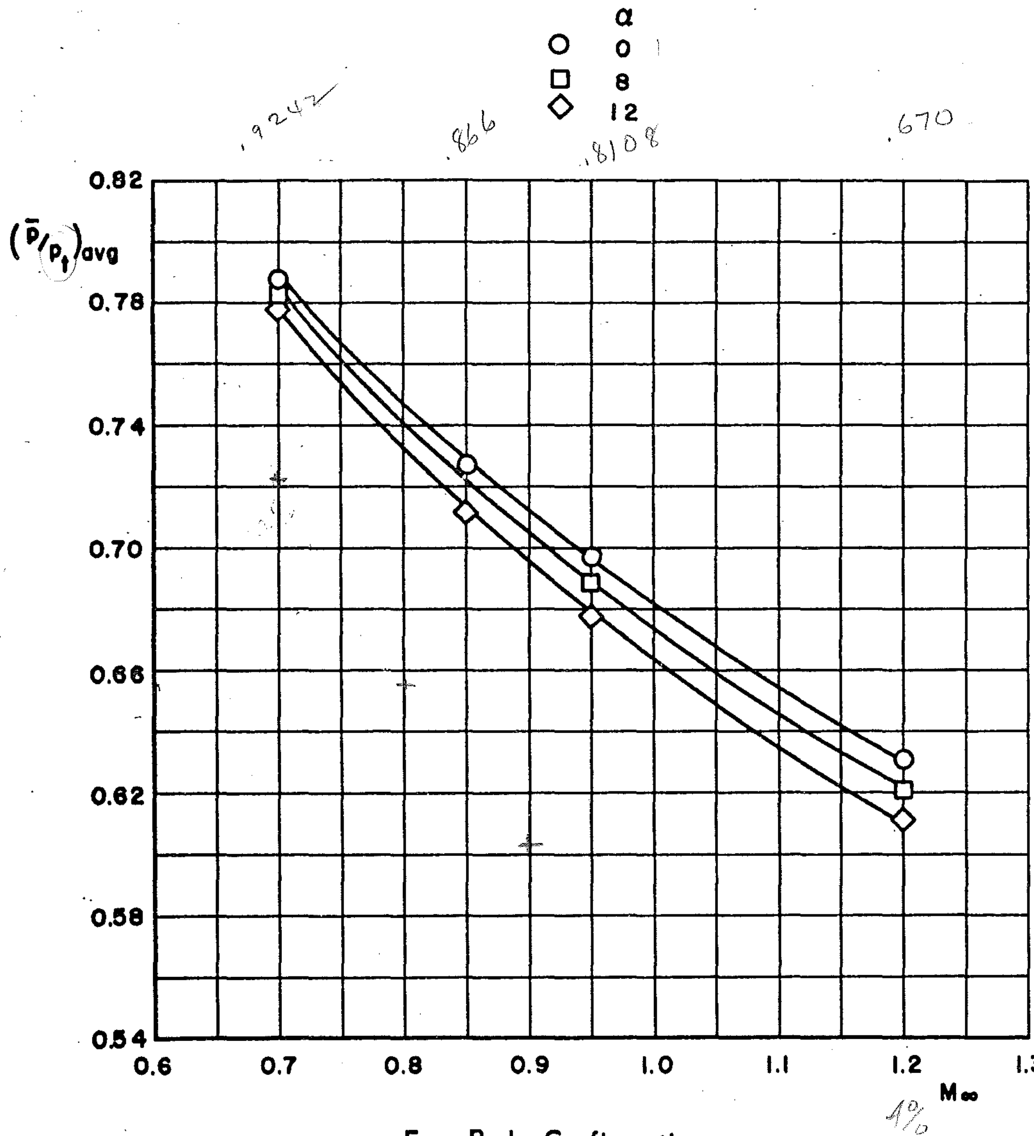
a. Single-Probe Configuration

Fig. 9 Variation of Ratio of Average Probe Static Pressure to Average Probe Total Pressure with Mach Number



b. Two-Probe Configuration

Fig. 9 Continued



c. Four-Probe Configuration

Fig. 9 Continued

$-0.65677 + 1.76904\,(\bar{P}/P_5) = P_\infty/P_5$

$-0.37686 + 1.38287\,(\quad)$

.04/deg.

UNIFIED SUBSONIC - TRANSONIC FLOW SOLUTION FOR A CONE

CONE ½∠ = 20° $\gamma = 1.400$ $x/L \approx .4282$

$\alpha = -1°$

$\boxed{\alpha = 1°}$		$\boxed{\alpha = 0°}$		ΔC_p	
$C_p \approx .218$	$M_\infty = 0.70$	$C_p \approx .239$	$M_\infty = 0.70$	.021	.042
$C_p \approx .245$	$M_\infty = 0.80$	$C_p \approx .265$	$M_\infty = 0.80$	.020	.04
$C_p \approx .272$	$M_\infty = 0.90$	$C_p \approx .291$	$M_\infty = 0.90$	.019	.038
$C_p \approx .317$	$M_\infty = 1.00$	$C_p \approx .326$	$M_\infty = 1.00$	.009	
	$M_\infty = 1.10$				